Science of the Total Environment 863 (2023) 160748

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

WildHealthNet: Supporting the development of sustainable wildlife health surveillance networks in Southeast Asia

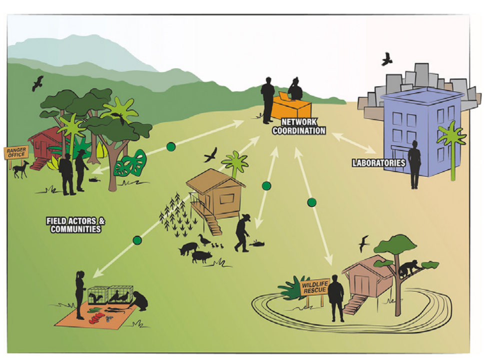
Mathieu Pruvot [a,b,*,1], Emily Denstedt [c,1], Alice Latinne [d], Alice Porco [e], Diego Montecino-Latorre [a], Kongsy Khammavong [c], Phonesavanh Milavong [c], Souchinda Phouangsouvanh [c], Manoly Sisavanh [c], Nguyen Thi Thanh Nga [d], Pham Thi Bich Ngoc [d], Vo Duy Thanh [d], Sokha Chea [e], Sreyem Sours [e], Phouvong Phommachanh [f], Watthana Theppangna [f], Sithong Phiphakhavong [f], Chhuon Vanna [g], Kry Masphal [g], Tum Sothyra [h], Sorn San [i], Hong Chamnan [j], Pham Thanh Long [k], Nguyen Thi Diep [k], Vu Trong Duoc [l], Patrick Zimmer [m], Kevin Brown [m], Sarah H. Olson [a,1], Amanda E. Fine [a,1]

[a] *Wildlife Conservation Society, Health Program, Bronx, NY, USA*
[b] *University of Calgary, Faculty of Veterinary Medicine, Calgary, AB, Canada*
[c] *Wildlife Conservation Society, Lao PDR Country Program, Vientiane, Laos*
[d] *Wildlife Conservation Society, Viet Nam Country Program, Hanoi, Viet Nam*
[e] *Wildlife Conservation Society, Cambodia Country Program, Phnom Penh, Cambodia*
[f] *National Animal Health Laboratory, Department of Livestock and Fisheries, Vientiane, Laos*
[g] *Department of Wildlife and Biodiversity, Forestry Administration, Phnom Penh, Cambodia*
[h] *National Animal Health and Production Research Institute, Phnom Penh, Cambodia*
[i] *General Directorate of Animal Health and Production, Phnom Penh, Cambodia*
[j] *General Directorate of Natural Protected Areas, Phnom Penh, Cambodia*
[k] *Department of Animal Health, Ministry of Agriculture and Rural Development, Hanoi, Viet Nam*
[l] *National Institute of Hygiene and Epidemiology, Hanoi, Viet Nam*
[m] *Canadian Wildlife Health Cooperative, Saskatoon, SK, Canada*

HIGHLIGHTS

- WildHealthNet (WHN) operationalizes a One Health approach to build national Wildlife Health Surveillance (WHS) systems
- WHN supports the development of WHS policy, capacity, and data management
- WHN addresses a need for better monitoring of wildlife health, and early outbreak detection and response
- WHN provides an iterative roadmap to support the expansion of local WHS networks

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Rafael Mateo Soria

Keywords:
Surveillance
One Health

ABSTRACT

Wildlife and wildlife interfaces with people and livestock are essential surveillance targets to monitor emergent or endemic pathogens or new threats affecting wildlife, livestock, and human health. However, limitations of previous investments in scope and duration have resulted in a neglect of wildlife health surveillance (WHS) systems at national and global scales, particularly in lower and middle income countries (LMICs).

* Corresponding Author: 3280 Hospital Dr NW, Calgary, AB, Canada.
E-mail address: mpruvot@ucalgary.ca (M. Pruvot).
[1] Equal contributions.

http://dx.doi.org/10.1016/j.scitotenv.2022.160748
Received 17 June 2022; Received in revised form 29 November 2022; Accepted 3 December 2022
Available online 10 December 2022

Wildlife disease
Pathogen
Network

Building on decades of wildlife health activities in LMICs, we demonstrate the implementation of a locally-driven multi-pronged One Health approach to establishing WHS in Cambodia, Lao PDR and Viet Nam under the WildHealthNet initiative. WildHealthNet utilizes existing local capacity in the animal, public health, and environmental sectors for event based or targeted surveillance and disease detection. To scale up surveillance systems to the national level, WildHealthNet relies on iterative field implementation and policy development, capacity bridging, improving data collection and management systems, and implementing context specific responses to wildlife health intelligence.

National WHS systems piloted in Cambodia, Lao PDR, and Viet Nam engaged protected area rangers, wildlife rescue centers, community members, and livestock and human health sector staff and laboratories. Surveillance activities detected outbreaks of H5N1 highly pathogenic avian influenza in wild birds, African swine fever in wild boar (*Sus scrofa*), Lumpy skin disease in banteng (*Bos javanicus*), and other endemic zoonotic pathogens identified as surveillance priorities by local stakeholders. In Cambodia and Lao PDR, national plans for wildlife disease surveillance are being signed into legislation.

Cross-sectoral and trans-disciplinary approaches are needed to implement effective WHS systems. Long-term commitment, and paralleled implementation and policy development are key to sustainable WHS networks. WildHealthNet offers a roadmap to aid in the development of locally-relevant and locally-led WHS systems that support the global objectives of the World Organization for Animal Health's Wildlife Health Framework and other international agendas.

1. Introduction

There is a global understanding that the health of humans, animals, plants, and the environment are intrinsically connected and are profoundly impacted by human activities (de Sadeleer and Godfroid, 2020; World Health Organization et al., 2015), which constitutes the One Health approach (Gruetzmacher et al., 2020). In March 2022, the Food and Agriculture Organization of the United Nations (FAO), the World Organization for Animal Health (WOAH), and the World Health Organization (WHO), signed a “Quadripartite” Memorandum of Understanding along with the United Nations Environment Programme (UNEP) reaffirming the importance of the environmental dimension in the context of One Health collaboration (Food and Agriculture Organization of the United Nations et al., 2022).

Wildlife species are vulnerable to direct health threats and the loss of ecosystem integrity, with significant cumulative effects on biodiversity conservation (White and Razgour, 2020). The anthropogenic declines of the planet's species and ecosystems, along with encroachment of humans into wild places, have provided increased opportunities for disease emergence (Kuchipudi et al., 2022; Russell et al., 2020), with serious impact on marine and terrestrial wildlife species conservation (Blehert et al., 2009; Fisher and Garner, 2020; Harvell et al., 2019). Wildlife are also potential reservoirs of pathogens (including zoonotic), and an important sentinel for emerging infectious diseases in humans. Outbreaks of diseases originating in wildlife such as Ebola virus disease, SARS, and COVID-19 have served as devastating reminders that in order to protect human health, we must monitor and reduce the risk of emerging zoonoses from wildlife (Keatts et al., 2021; Kuisma et al., 2019; Li et al., 2021). The cost of primary prevention of zoonotic pathogen spillover, through actions such as reducing deforestation and halting commercial wildlife trade, is far less devastating than the lives lost and economic fallout of zoonotic pandemics (Bernstein et al., 2022; Dobson et al., 2020; Vora et al., 2022).

Beyond emerging diseases, the understanding of major endemic and neglected tropical diseases in resource-constrained countries remains hindered by a lack of surveillance in both humans and potential wildlife reservoirs to inform management strategies (Tambo et al., 2014). Other pathogens shared between livestock and wildlife, such as African swine fever (ASF) virus and Peste des petits ruminants (PPR) virus, can have catastrophic consequences for both agricultural livelihoods and susceptible wild species (Denstedt et al., 2021; Fine et al., 2020; Luskin et al., 2021; Pruvot et al., 2020). Wildlife health monitoring is, therefore, essential to generating the data required to identify health threats to wildlife, livestock, and/or humans (Food and Agriculture Organization of the United Nations et al., 2019), and to facilitate integration of these data into a One Health approach to prevention or management of health risks.

Wildlife Health Surveillance (WHS henceforth) and WHS networks refer to long-term operational networks of stakeholders monitoring diseases (of either infectious or non-infectious etiologies) or other health indicators in wildlife for the purpose of guiding management decisions and interventions. The importance of WHS for conservation, ecosystem integrity, sustainable development, public health, and biosecurity has prompted the World Organization for Animal Health (WOAH/OIE) to encourage member countries to have wildlife disease monitoring and notification systems in place, most recently in the WOAH Wildlife Health Framework (WOAH, 2021). WHS in coordination with animal and public health sectors is also included as a core competency in the International Health Regulation and Global Health Security Agenda (Global Health Security Agenda, 2018; WHO, 2008). WHS networks have been formally established in fewcountries (Stephen et al., 2018; Chame et al., 2019; Woods et al., 2019) and they have proved their value to protect wildlife and human health (Brand, 2013). However, investments in building and operationalizing WHS networks, and the human and technical resources to do so, are lacking in the areas where they are most urgently needed - i.e. places with rapid encroachment on high biodiversity biomes and hotspots of disease emergence (Allen et al., 2017; Machalaba et al., 2021).

Along with the typical challenges known about conducting WHS (e.g. Lawson et al., 2021; Ryser-Degiorgis, 2013; Stallknecht, 2007), two significant and inter-linked paradoxes have limited the establishment of effective, sustainable surveillance networks globally: 1) from a governance perspective, operational WHS requires both strong bottom-up and top-down approaches; 2) from a scale perspective, WHS networks must reach key local interfaces where spillovers occur, while at the same time expand and integrate into regional and global networks. Governance is a well-recognized impediment to WHS, with a lack of clarity on mandates and responsibilities between governmental entities (Sleeman et al., 2012; Stephen et al., 2018). The mandate for WHS is typically an area of contention, as responsibilities for animal health, wildlife, and protected areas are usually shared between multiple ministries without any clear policy guidance for wildlife health (Stephen et al., 2018). Concomitantly, if WHS is to be effective against the spread of newly emerging pathogens or the detection of unusual health events, surveillance needs to happen as close as possible to where these events may occur. This requires scaling up data collection to all professionals working and all communities living in the critical areas of interest, harnessing strong bottom-up approaches (Kutz and Tomaselli, 2019; Peacock et al., 2020) followed by integration of locally-generated, standardized data into intelligence and policy of regional and global relevance (VanderWaal et al., 2017). We believe that the sustainability issues faced by most existing approaches to WHS are the result of an unbalanced investment in the top-down and bottom-up components, and of the difficulty in scaling up local initiatives into regional and global surveillance efforts.

The Lower Mekong is a region of high biodiversity and high human density and one that faces considerable conservation threats (Wilcove et al., 2013). Major drivers of pathogen spillover from wildlife to humans and livestock – deforestation, land-use change, and wildlife trade – are commonplace (Allen et al., 2017; Coker et al., 2011). This region is, therefore, a high priority for the development of long-term WHS programs. For over ten years, Cambodia, Lao PDR, and Viet Nam have been engaged in major initiatives focused on pathogen surveillance in wildlife. These efforts were accelerated broadly by the emergence of highly pathogenic avian influenza due to influenza A virus H5N1. Global viral discovery initiatives identified multiple viruses of potential public health concern, such as coronaviruses, circulating in wildlife (Delaune et al., 2021; Huong et al., 2020; McIver et al., 2020; Nga et al., 2022), and contributed to capacity bridging in animal and human health laboratories (Kelly et al., 2021). Initial efforts were made to address the need for a framework sustaining WHS through collaborations with the governments of Cambodia and Lao PDR (LACANET 2014-2018, funded by the Commission of the European Union). Despite these advances, the focus and resources of governments largely remained directed towards monitoring and mitigating disease in livestock and people, and mandates for wildlife health in these countries had yet to be established. Subsequently, with the support of the United States Defense Threat Reduction Agency - Biological Threat Reduction Program, Wildlife Conservation Society (WCS) and government partners sought to formally develop and operationalize WHS networks in Cambodia, Lao PDR, and Viet Nam through the WildHealthNet initiative.

In this paper, we describe the conception and implementation of WildHealthNet (2018–2022), a model which can be adapted for use in other countries and adopted by governments, wildlife conservation actors, civil society organizations, and communities. Lastly, we discuss how WildHealthNet will be valuable to international organizations to meet objectives of improving WHS and holistic One Health surveillance objectives globally.

2. Material and methods

2.1. General approach

At the onset of the WildHealthNet initiative, no nationally approved agreements existed between the animal health and the environmental sectors in Cambodia, Lao PDR, or Viet Nam for coordinating pathogen surveillance in wildlife or monitoring, managing, or responding to wildlife morbidity and mortality events. Involvement of the environmental sector in wildlife health-related events was extremely limited. Conversely, livestock and human health agencies usually have little mandate or authority to operate in natural areas or in relation to wildlife issues. WOAH Focal Points for wildlife within the animal health sector (Lao PDR and Viet Nam) or the forestry sector (Cambodia) are responsible for reporting WOAH-listed diseases in wildlife (https://www.woah.org/en/what-we-do/animal-health-and-welfare/animal-diseases/) detected in their country. Their agencies, however, are often not provided with the human and financial resources necessary to conduct WHS broadly and consistently. The approach of WildHealthNet, in absence of an established policy framework, was to demonstrate the feasibility of a multi-sectoral and inter-ministerial WHS system, while building on existing and durable field and laboratory capacity. Doing so, we aimed to provide a solid proof of concept, a pilot for an effective WHS network, and a new basis for policy discussions and development. WildHealthNet began with an initial consultative process in the development phase to define partners in each country, primarily engaging each local government, but also involving non-governmental bodies. The primary objectives of this consultative phase were to identify interest in and potential contributions of partners to developing a WHS network at a national level and to identify key surveillance objectives.

WildHealthNet's strategy to build and operationalize each country's WHS network focused simultaneously on five components: (1) piloting the network through different priority surveillance activities; (2) policy development to formalize stakeholders' roles and responsibilities (3) capacity bridging at all levels of the network, (4) developing and deploying wildlife health data collection and data management tools; and (5) One Health coordination to respond to wildlife health intelligence.

2.2. Piloting surveillance

All the countries included a component of general scanning (passive) surveillance and of targeted surveillance. General scanning surveillance was structured to detect morbidity and mortality events in wildlife, both free-ranging and captive. Targeted surveillance was conducted on predetermined pathogens (Table 1) as prioritized during planning discussions with governmental partners in each country and chosen from a list of especially dangerous pathogens provided by the US federal government (https://www.selectagents.gov/sat/list.htm). Targeted surveillance activities allowed for the collection of samples and data to facilitate stakeholder experiential learning, and informed the development and formalization of national WHS policy (discussed below). Broadly, the scale of general surveillance components of WildHealthNet was more substantial as it is critical in defining the network structure and relationship between stakeholders.

When piloting general scanning surveillance, a network of field actors most likely to come across sick or dead wildlife, including protected area rangers, communities adjacent to wildlife habitat, wildlife rescue centers, and other government and non-government entities (e.g. conservation scientists), were involved (Fig. 1). Reporting lines, specimen collection and submission procedures, and in-country laboratories designated to receive wildlife specimens were discussed and agreed upon by each field actor and central government representatives in accordance with existing protocols and reporting mechanisms (e.g., livestock sector lines of communication, protected area chain of command, etc.). Additionally, to facilitate effective coordination among each branch of the network and ensure its sustainability, one WHS Network Coordinator was instituted within government agencies in Lao PDR and Cambodia under their respective WOAH National Focal Points for wildlife, while in Viet Nam, network coordination was a joint effort between WCS staff and the WOAH National Focal Point for wildlife within the Department of Animal Health. Procedures and protocols were then iteratively optimized based on “on-the-ground” realities, effectiveness, practicality, constraints, and acceptability. In some cases, general scanning surveillance via these mechanisms was trialed first in specific protected areas, ones in which ranger patrol and wildlife monitoring teams had pre-existing technical support from WCS, before

Table 1
Surveillance targets in each country and corresponding surveillance strategies.

Pathogen	Surveillance strategy
African swine fever virus (Cambodia, Lao PDR, Viet Nam)	Wildlife trade market surveillance; participatory community surveillance; forest ranger patrols for fecal sampling
Avian influenza virus (Cambodia, Lao PDR, Viet Nam)	Wildlife trade market surveillance; environmental sampling at poultry - wild bird interface in wetlands
Rickettsiales (Lao PDR, Viet Nam)	Wildlife trade market surveillance; rodent live-trapping; sampling of confiscated rodents from wildlife trade
Nipah virus (Cambodia)	Non-invasive sampling of flying fox *(Pteropus* spp.*)* colonies (urine on plastic tarps)
Hantaviruses (Viet Nam)	Wildlife trade market surveillance; rodent live-trapping
Coronaviruses (Viet Nam)	Bat sampling (live-sampling and guano collection); Confiscation of illegally traded pangolins, civets, and tigers

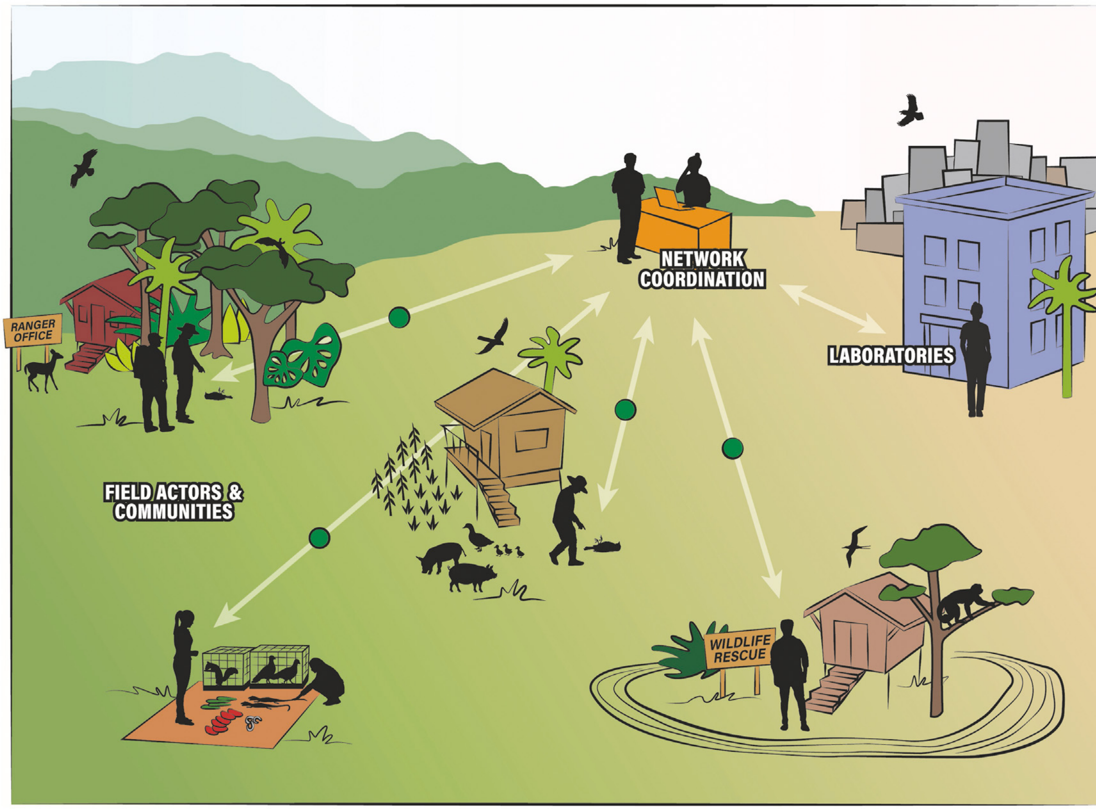


Fig. 1. Overview of WHS network structure and information flow among actors.
"Field actors & communities" included protected area rangers, small-holder farmers, wildlife trade vendors, hunters, wildlife rescue centers, and other stakeholders interacting with wildlife. *"Network coordination"* included Network Coordinators in each country, WOAH Focal Points for Wildlife, Wildlife Health Working Groups. Double-arrows represent transfer of samples and information. Local focal points, local government officers, and other sector-specific points of contact facilitating transfer of information are represented by a green dot on double-arrows.

scaling up to other areas of the country (Fig. 2). In some of these pilot protected areas, a local focal point was designated on-site to coordinate sample and information transfer from the protected area to the laboratory and network coordinators.

2.3. Policy development

Our objective in each country was to develop comprehensive Standard Operating Procedures (SOPs) for WHS that could be integrated into national policy. Field surveillance activities were conducted in parallel to inform and optimize SOP development, providing on-the-ground examples to discuss in cross-sectoral meetings. WildHealthNet facilitated the development of SOPs through consultation with stakeholders from the animal health and forestry/environment sectors, as well as non-government field and laboratory partners.

2.4. Capacity bridging

While piloting WHS network components, capacity among network stakeholders was strengthened both through formal training and informal on-the-job support and mentoring, at all levels of the network (e.g., forest rangers, government livestock officers, conservation field staff, laboratory technicians, and WHS Network Coordinators). Standard core competencies for WHS and training materials in local languages were developed by WildHealthNet for each main stakeholder group to allow harmonization across countries. While training content was standardized, training delivery was piloted and tailored for different audiences depending on their level of experience and role within the network, as well as language and cultural background. This complemented the WOAH Focal Point training (WOAH, 2018, 2017a, 2017b, 2015, 2010) with a stakeholder-specific delivery system, and provided government partners with the necessary resources to conduct future trainings and grow their respective WHS networks.

2.5. Data collection and management

The access to and use of robust and efficient tools for collection and management of standardized wildlife health data was identified as a key gap in each country. Desired features of such tools included long-term sustainability, affordability, simplicity, and the possibility to leverage existing field presence. Further, the WHS networks needed flexible tools to accommodate data from diverse surveillance objectives (e.g. targeted or scanning surveillance, participatory surveillance, complex study designs, outbreak investigations) and types (e.g., geographic information, necropsy reports, pictures, test results, supporting files), to facilitate basic reporting, complex queries, and data sharing; and assure data safety and security.

The Spatial Monitoring and Reporting Tool (SMART; www.smartconservationtools.org) and the Wildlife Health Intelligence Platform (WHIP; Canadian Wildlife Health Cooperative/University of Saskatchewan, Canada) were selected for data collection and data management, respectively. SMART is a suite of open-source technological tools developed for law enforcement in protected areas by the SMART Consortium. It is used by more than one thousand sites located in more than 70 countries (SMART Partnership, 2021). SMART consists of computer software (SMART Desktop), a mobile device application

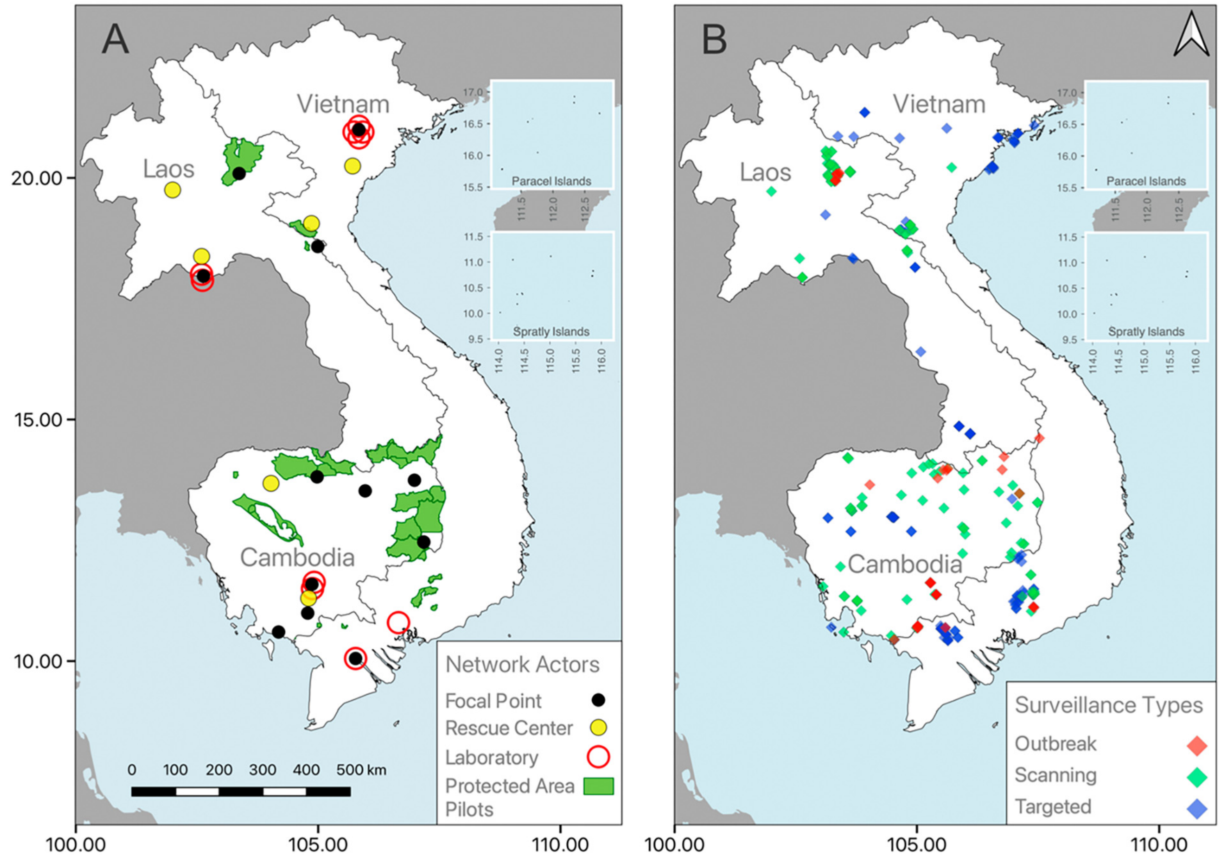


Fig. 2. A) Distribution of network focal points, wildlife rescue and rehabilitation centers, laboratories, and protected area pilot sites.
B) Surveillance activities taken place across Cambodia, Lao PDR and Viet Nam between 2019 and 2022.

(SMART Mobile), and a server (SMART Connect). Standardized data models can be created in SMART Desktop and loaded on SMART Mobile and used to easily record a wide range of information in the field. SMART Connect facilitates instant communication between SMART Mobile and SMART Desktop, permitting real-time information transfer from the field to centralized focal points. WHIP is a database iteratively developed over 25 years by the Canadian Wildlife Health Cooperative (CWHC; Leighton et al., 1997) and was chosen for the WildHealthNet initiative following a review of existing wildlife health information management systems. The current web-based version of WHIP manages data from Canada's five provincial nodes, as well as other external users. The platform organizes data as georeferenced wildlife health events that include information of the event location, the observed wildlife, the specimens (animals) collected or sampled, and diagnostic procedures and/or necropsies conducted on the specimens or their samples.

The selected tools were piloted during this initiative by multiple network stakeholders. The tools were designed and modified based on, and informed by, field activities conducted by end-users in each country including WCS wildlife health teams and rangers from a set of protected areas in Cambodia and Lao PDR.

2.6. One Health coordination to respond to wildlife health intelligence

Clearly connecting the information generated by surveillance efforts to tangible management response is essential to demonstrating value and ensuring sustainability of WHS in any country. WildHealthNet built upon long-term relationships with national government partners in each country to facilitate decision-making in response to wildlife health events, and coordinated with One Health platforms and other cross-sectoral groups.

3. Results

3.1. Piloting surveillance structure and operations

General scanning surveillance, focused on wildlife mortality and morbidity events, was operationalized across the three countries (Fig. 2) based on a network of actors coordinating event detection, reporting, laboratory diagnostics, and communication (Fig. 1). Sites to pilot general scanning surveillance (Lao PDR $n = 4$, Cambodia $n = 18$, Viet Nam $n = 8$) were chosen based on the presence of wildlife, presence of personnel monitoring the area, and the relationships with those partners. In addition to protected areas (Table S1), wildlife rescue and rehabilitation centers such as Phnom Tamao Wildlife Rescue Center, Angkor Center for Conservation of Biodiversity, Lao Conservation Trust for Wildlife, Save Viet Nam's Wildlife, and Free the Bears were encouraged to report unusual events of wildlife mortality or morbidity. Operationalizing and expanding WHS networks in this manner led to the detection in traded and free-ranging wildlife of multiple pathogens of significance to wildlife, livestock, and/or human health (see Table S2 in Supplementary Material). Outbreak investigations were conducted in response to mass mortalities and clusters of sick and/or dead wildlife in coordination with government partners (see Text Box).

Targeted surveillance activities were an opportunity to discuss and illustrate different approaches to wildlife disease data collection with partners. A detailed description of the design and outcomes of these targeted surveillance programs is beyond the scope of this article and will be the object of separate publications, but Table 1 provides a summary of the objectives and corresponding surveillance strategies employed.

Case Study 1: African Swine Fever in Wild Boar.

Fig. B1: Participatory mapping of ASF outbreak with local government staff and community members.

ASF virus is a highly contagious pathogen that infects both wild and domestic pig species and leads to hemorrhagic fever with high mortality rates. The early stages of WildHealthNet's development coincided with the first introduction of ASF into the domestic pig populations across Southeast Asia in 2019. To better understand and mitigate the ASF epidemic in each country, it was critical to determine whether ASF could be detected in the wild boar population, and their capacity to act as a reservoir as they do in Eastern Europe (Cukor et al., 2020; Probst et al., 2017). In rural communities throughout Lao PDR, Cambodia, and Viet Nam it is commonplace to raise free-ranging pigs, generating opportunity for contact with wild boar in adjacent habitat and thus creating an interface for ASFV transmission. Through participatory community engagement and surveillance on the ground by forest rangers patrolling protected areas in each country, the WildHealthNet initiative was able to detect ASF in free-ranging wild boar for the very first time in Southeast Asia following initial spread in the domestic pig population (Denstedt et al., 2021) and pilot what would be the future reporting mechanisms for wildlife morbidity and mortality events.

Case Study 2: Avian Influenza in Wild Birds.

Fig. B2: Wild bird carcass collection and destruction following HPAI H5N1 outbreak.
In early 2021, government rangers and community members in southeastern Cambodia detected a series of wild bird mass mortality events involving over 2000 wild birds, the majority of which were Asian openbill storks *(Anastomus oscitans)*. A multi-sectoral investigation involving environmental and animal health government agencies, conservation organizations, and local authorities was conducted to determine the cause of the mortality events. Highly pathogenic avian influenza (HPAI) H5N1 was ultimately confirmed by the national laboratory. The network was utilized to coordinate response efforts, such as follow up sampling, biosecurity, and decontamination, across different agencies and notify relevant stakeholders throughout the country and Lower Mekong region.
Following the detection of HPAI H5N1 in Cambodia, multi-stakeholder avian influenza investigations took place in southern Viet Nam (Dong Thap province) near the Cambodian border. Bird populations were surveyed in collaboration with the Dong Thap Provincial Department of Animal Health and other WHS Network partners. Sick and dead free-ranging wild birds were detected and sampled in Tram Chim National Park and tested positive for HPAI H5N1.
Additional protected areas, including three national parks in Viet Nam, and other network partners throughout the region, were requested to monitor for wild bird mortality events, however no further unusual mortalities were reported.

Case Study 3: Lumpy Skin Disease in Banteng.

Fig. B3: An image captured by trail cameras of a case of LSDV in banteng (*Bos javanicus*).
Lumpy skin disease virus (LSDV) was introduced to domestic cattle populations in Southeast Asia in 2021 (International Society for Infectious Diseases, 2021) and first detected in Cambodia, Lao PDR and Viet Nam in June 2021, May 2021, and October 2020, respectively (OIE-WAHIS reports, WOAH). In June and August 2021, Thailand reported cases of the disease in endangered gaur (*Bos gaurus*) and banteng (*Bos javanicus*), respectively, raising concerns in the wildlife conservation community. The regional network was utilized to alert protected area and conservation staff about the risk of disease to these threatened populations and report any potential cases. In September 2021, a banteng with scabs and skin

nodules suspicious for LSDV was seen by community rangers in a protected area in northern Cambodia. Following notification of the network, government partners arranged for a provincial veterinarian to collect samples from the animal, which tested positive for LSDV. Controlling the disease in livestock is critical to preventing transmission to wild bovids. With the limited resources to implement a targeted vaccination campaign, the animal health department collaborated with the wildlife conservation community, who supported the purchase of LSDV vaccinations for domestic cattle in and around protected areas with banteng and gaur, to help prevent LSDV transmission in these critically endangered populations of wildlife.

3.2. Policy development

In parallel with piloting surveillance mechanisms in the field, project partners, government counterparts, and One Health stakeholders co-developed policy instruments in each country to support the sustainability and institutionalization of their respective WHS networks. Workshops were organized to share lessons learnt from pilot activities, refine surveillance objectives, and draft Standard Operating Procedures (SOP) for national wildlife health surveillance (see Table S3 in Supplementary Material). The "Standard Operating Procedure for Wildlife Health Surveillance in Lao PDR", initiated in 2017 under the EU-funded LACANET project and further developed during WildHealthNet, was approved and signed by Lao PDR's Ministry of Agriculture and Forestry in August 2022. This document formalizes and guides general surveillance procedures, data management, reporting, and decision-making, including through the proposed establishment of a new National Wildlife Health Surveillance Committee as the central governmental body for WHS. In Cambodia, WHS efforts have been led by the Wildlife Health Surveillance Network Working Group formed under WildHealthNet in 2019. The group consists of representatives from the forestry, environmental, and animal health sectors, laboratories, wildlife rescue centers, and conservation organizations, and aims to facilitate communication, information sharing, and coordination across stakeholders. Because responsibilities for wildlife and disease outbreak experience differed across the agencies, it was determined that decisions regarding outbreak investigation, diagnostic test selection, data analysis, management and response be made collectively by the working group. The working group played an essential role in drafting the SOP for WHS in Cambodia. The process of developing a sustainable WHS network started later in Viet Nam, where partner agencies are building ties through active engagement in surveillance activities to facilitate WHS framework and policy development. Although each country was at a different stage in the construction and adoption of these policies at the conclusion of the project, network stakeholders all have made substantial progress on defining roles and responsibilities for WHS.

3.3. Capacity bridging efforts

WildHealthNet developed training material tailored to stakeholder groups essential to a functional network, and the Core Competencies identified for each group (available at https://oneworldonehealth.wcs.org/Initiatives/WildHealthNet/WildHealthNet-Resources.aspx). Forest rangers, as an example, received practical training in basic wildlife sampling, biosafety, and recording information on events they may encounter when patrolling a protected area. Activities included Personal Protective Equipment demonstrations, outdoor wildlife mortality/morbidity simulations, sample collection practice with cadavers, as well as formal and informal post-training evaluations (see Table S4 in Supplementary Material). Government livestock officers (e.g. Cambodian Applied Veterinary Epidemiology Training graduates [CAVET]; district animal health officers in Lao PDR), received more specialized in-depth training of outbreak investigation and necropsy. The different stakeholders learned data collection and management tools (see "Data collection and management" section below) using both simulation exercises and on-the-ground practice during real surveillance activities. The sets of standardized training materials developed and utilized by WildHealthNet during the life of the project were handed over to government partners, equipping them with the tools and resources needed to sustain and expand these networks more widely.

3.4. Data collection and management

We developed SMART data models specific to WHS field data collection (SMART for Health) and targeting user groups with different levels of training, from park rangers to specialized surveillance teams. These data models record information from the spatial location of a wildlife health event down to the samples collected from each animal or from the environment. At the time of writing, focal points for WHS stationed in two of Lao PDR protected areas, Nam Et – Phou Louey National Park and Phou Sithon Endangered Species Conservation Area, have begun using SMART for Health to enter data on sick or dead wildlife detected during ranger patrols. Forest rangers and biodiversity monitoring teams in three protected areas in Cambodia received training which introduced the SMART for Health model. In Viet Nam, the new national SMART data model was released by the Department of Protected Area Management (DOPAM) in October 2021, and includes fields allowing the collection of wildlife health information. As of November 2021, this new data model has been tested in six protected areas with the support of Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH (Table S1).

WHIP, our central database, was customized for WildHealthNet and expanded the basic data structure (Project>Event>Specimen>Samples) to include environmental specimens and track diagnostic tests to individual samples. The database can also accommodate other data types including pictures, videos, and metadata.

While SMART and WHIP are valuable as independent data collection and management tools, respectively, their integration can deliver actionable analytics by facilitating the recording, real-time transmission, and storage of standardized wildlife health information. Therefore, SMART for Health was designed so collected data can be easily transferred to WHIP and an Application Programming Interface (API) is currently in development to facilitate SMART-to-WHIP interoperability and on-the-fly data transfer. This API will support potential future integration with other data management systems as needed.

3.5. One Health coordination and response

To keep partners engaged in and updated on network progress, information detailing outbreaks, training, and One Health coordination activities were shared with network members and One Health partners through a newsletter disseminated up to four times annually (see Table S5 in Supplementary Material). The WHS working groups formed in each country were instrumental in coordinating a One Health response to wildlife health events. For instance, the Wildlife Health Surveillance Network Working Group in Cambodia was utilized to coordinate risk assessments, response efforts, and mitigation measures during various wildlife outbreaks (see Text box case studies 2 and 3). Similarly, in Viet Nam, close coordination between wildlife rescue and rehabilitation centers, protected area management boards and the Department of Animal Health led to effective zoonotic disease surveillance in wildlife confiscated from the illegal wildlife trade. In Lao PDR, communication and planning for potential human-to-wildlife transmission of SARS-CoV-2 took place between captive wildlife facilities, WCS, the National Animal Health Laboratory, and a partner lab conducting COVID-19 testing in humans. Finally, WHS network members were also engaged in other decision-making and policy processes relevant to zoonotic disease surveillance, emerging infectious disease preparedness, and One Health coordination, ensuring the WHS network was consistently embedded into national-level One Health planning.

4. Discussion

4.1. Building the network

The WildHealthNet initiative provided a large-scale demonstration of "One Health in Action" and its benefits in operationalizing wildlife health surveillance. The WildHealthNet approach was built upon a foundation of long-standing relationships with public health, animal health, and environment sector agencies in each country, previous One Health efforts in the Southeast Asia region (Kelly et al., 2017; LACANET, 2016), other global WHS initiatives (Stephen, 2015; WOAH, 2021), existing national structures, and the landscape-based conservation approach of WCS combined with longstanding wildlife health professionals distributed globally (Fig. 1).

Empowering local institutions to take ownership of the initiative was critical. Encouraging each country's government and local stakeholders to set their own core surveillance objectives, rather than having objectives defined by external bodies (international partner or funding agency), promotes stronger project ownership and contributes to decolonizing global cooperation (Food and Agriculture Organization of the United Nations et al., 2019). Furthermore, ground-level expertise with local in-country teams was found to be entirely essential and complementary to guidelines and standards developed by international bodies. A "boots on the ground" approach and engagement with local stakeholders is imperative to develop and customize a national-level WHS network, one that is rooted in local knowledge and practices, and answers to the specific needs and objectives of national government and local communities.

Finally, our approach to building a WHS network in each country was not a linear process but instead was highly iterative and emulates progressive implementation (Food and Agriculture Organization of the United Nations et al., 2019), with rapid and progressive cycles of pilot field implementation, evaluation, and protocol/policy adjustments. This ensured the bottom-up identification of practical and sustainable strategies and protocols, and their inclusion in national standard operating procedures and policies. This also contributed to building a strong relationship with field actors by ensuring that their concerns were heard and acted upon (Chea et al., 2021). Because of differences between countries in baseline capacity, prior wildlife surveillance projects, prior policy development efforts, there were local difference in the implementation of the WildHealthNet approach and the outcome at the end of this implementation period. The WildHealthNet approach strives to be complementary of and consistent with frameworks and guidelines established by international organizations, in particular with the WOAH Wildlife Health Framework (WOAH, 2021). In many ways, the WildHealthNet processes are a roadmap to achieve these standards and best practices.

4.2. Capacity bridging

Wildlife health event investigation and surveillance activities involve a broad diversity of One Health actors, with varying levels of experience, participating in event detection, outbreak investigations, sampling, reporting, laboratory processing, data management, analysis, risk assessment, communication and mitigation. Each group of actors requires customized training depending on their level of learning, and what their expected responsibilities would be within the network. Protected area rangers do not hold the same level of experience or expected responsibility when responding to a wildlife health event as do actors with a background in animal health, and country-to-country variation among ranger skill sets exists. As part of the WildHealthNet project, we identified standard sets of core competencies as a starting point for specific roles within each national WHS network, which could then be adapted to fit the local context. Core competencies and associated training material allowed us to standardize training across countries, while also customizing it to different actors and field- or facility-specific situations. Training material and content was designed to be participatory and was progressively adjusted to optimize the acceptability of surveillance procedures across the network (Chea et al., 2021).

Government institutions and external partners working as side-by-side learners and educators fosters investment in local leadership and mutual accountability. Focused individual mentorship for WHS Network Coordinators was critical to project implementation. Much of the training was provided "on-the-job" (e.g. receiving reports of event detections, specimen data management, reporting back diagnostic results to partners, planning training for network actors etc.). Network Coordinators in Lao PDR and Cambodia were also intimately involved in delivering the various types of training to network actors, following a training-of-trainer model to establish a sustainable model. Maintenance of a WHS Network Coordinator and integration of this role as part of the national governments will be essential to ensure continued coordination of operations between sectors and sustainability of the network. Plans for integration of this role formally as part of national government staff were discussed early in the project, but remain a critical and pending decision point.

4.3. Data collection and management

The system developed and deployed during this initiative is timely and meets a global need for wildlife disease data collection and management in a standardized, practical manner (Artois et al., 2009; Lawson et al., 2021, WOAH, 2018). SMART for Health and WHIP are at the service of specific surveillance needs, but can be easily adapted and used for WHS in different contexts, highlighting the potential to quickly expand SMART for Health and wildlife health monitoring globally.

Our use of existing and well-established platforms supports long-term sustainability of surveillance efforts as both tools have well-established IT support and funding. Nevertheless, logistical considerations include internet and computer access, and internet signal in remote places to facilitate real-time data transfer. While SMART is open-source, WHIP comes with financial expenses such as license and maintenance fees. Further, the human resources needed to update and manage SMART in computers, devices, and servers; connect with SMART and WHIP IT support; and enter, curate, maintain, manage, analyze, and share data collected with these systems have financial and training costs that should not be discounted. To ensure accessibility, SMART for Health was translated into Lao, Khmer, and Vietnamese, however the availability of specific technical terms in certain languages remains a challenge. Furthermore, varying degrees of comfort with digital devices among stakeholder groups may increase hesitancy in adoption. Adoption of new data platforms were sometimes further discouraged by previous national efforts to improve data management systems, particularly in the livestock health sector and/or laboratory setting (e.g. Laboratory Information Management Systems), even when a certain level of inadequacy for wildlife health was recognized. With both SMART and WHIP having developed APIs, integration of these systems are technically feasible, ensuring the use of specialized data management systems for different types of surveillance, while allowing communication and coordination between One Health sectors and systems as required.

SMART and WHIP represent the most complete wildlife information management system to our knowledge, and these two platforms are suggested as best practice standards in wildlife health data collection and management.

4.4. Lessons learned and next steps

The long-term commitment to One Health practices and policy development is essential to sustainable progress towards inter-sectoral collaboration, but challenged by 'short-term' project funding models and mechanisms (Stephen et al., 2018). Sustained funding mechanisms for these networks are lacking, particularly as health resources remain prioritized towards human and livestock health. The creation of national standard operating procedures for WHS, however, helped reframe the WildHealthNet initiative from a series of finite but often not sustained "project activities", to being part of national policy. Although specific roles and responsibilities need to eventually be clearly defined and assigned, shifting the conversation away from existing mandates to identifying potential contributions to WHS was helpful in collectively imagining a cross-sectoral surveillance system. Building on these existing frameworks (e.g., reporting lines, technical responses) was a practical and efficient strategy to facilitate the mapping and integration into a formal WHS network that encompassed each sector - public health, animal health, and environmental management.

Demonstrating the direct connection between surveillance activities and management actions (see descriptions in Text Box) was essential in highlighting the value of the surveillance system to stakeholders and securing confidence in how these networks could function in the long-term. It also showcased the value of greater integration of local communities as wildlife stewards, as well as the wildlife management and environmental sector in the One Health forum, given their direct physical proximity to wildlife populations, their intimate knowledge of local wildlife, wildlife habitat, and wildlife utilization practices (e.g., wildlife hunting and trade/trafficking).

Communication and reporting efficiency of wildlife health events and pathogens of concern, due to the sensitive nature of the implications for human and livestock health as well as livestock trade, was a commonly encountered challenge throughout WildHealthNet. Continued encouragement towards transparency and the benefits of early reporting, particularly in resource-limited settings, is strongly recommended so that efficient WHS networks can be realized and the necessary support can be harnessed.

Formal and standard evaluation frameworks should be used to assess the effectiveness of a network once fully operationalized (Food and Agriculture Organization of the United Nations et al., 2019). Initial steps were taken to adjust existing evaluation frameworks for WHS (Goutard et al., 2022; World Organisation for Animal Health, 2015), and baseline assessments were made at the start of the project in Cambodia (Chea et al., 2021), which will be repeated in the future. Formal cost-effectiveness or cost-benefit analyses remain a major gap across most WHS systems globally, and an important area of research going forward. Additional analysis of surveillance data in combination with wildlife population data will continue to improve our understanding of strengths and weaknesses (e.g. imperfect detection, bias) of morbidity-mortality data.

It should be noted that the large majority of this WildHealthNet initiative took place during the COVID-19 pandemic, which caused interruptions in field work, training, and in-person collaboration due to strict national lockdowns. It is unknown to what degree, if any, this hindered the pace of the networks' development. The authors encourage readers and future network developers to interpret the implementation timeline here in the context of the pandemic-related limitations. That being said, long-term commitment is essential in supporting the development of such surveillance systems. Specifically, long-term efforts allow progressive and multiple iterations of protocol drafting and pilot field testing before formalization of procedures. This approach lays solid foundations for network structure and processes, essential to scaling-up the system to the national level. Careful planning for transition out of a project, from project to project, or to fully government-led surveillance should be initiated early on to optimize the chances of sustaining project achievements.

5. Conclusions

The WildHealthNet model and the tools developed are translatable for use in other nations wanting to build their own WHS networks, and flexible enough to be adapted to any country context. Ultimately, and ideally, these various national systems may be linked to form cohesive WHS networks which operate at regional or global levels. We demonstrated that long-term commitment to iterative development, and paralleled implementation and policy development were all key to sustainability of WHS networks. Pandemic prevention must include surveillance measures and interventions as close as possible to the sources - where wildlife and wild places are disturbed. Restoring and maintaining integrity of ecosystems, reducing our encroachment on nature, and supporting countries in early detection of and early response to pathogens circulating in wildlife (zoonotic or not) are cost effective measures which address major planetary challenges we face today. The WildHealthNet approach comes at a critical time when the global need for systematic WHS has never been more apparent and broadly recognized. The WildHealthNet approach offers locally-driven solutions to meet global objectives (WOAH, 2021).

Data availability

The data that has been used is confidential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Dr. Hol Davun for his support through this project and honor his memory. We also would like to thank those working tirelessly on the ground and in the field to monitor and protect wildlife as part of this important network.

In Lao PDR, we would like to thank Dr. Santi Saypanya (Country Director, WCS Lao PDR), Phaisouk Phutthapanya and Saylom Luangmeexay (Department of Livestock and Fisheries, Lao PDR), Ninthita Vandydonesavanh (WCS Lao PDR), Dr. Matthew Robinson (LOMWRU), Free the Bears, the Lao Conservation Trust for Wildlife, and Sengsai Phonthasy, Chanthana Senaphanh, and Vilayvan Soukvilay (National Animal Health Laboratory, Lao PDR) for their support in the development of this network.

In Viet Nam, we extend our gratitude to Hoang Bich Thuy (WCS Viet Nam), Nguyen Thi Lan (Viet Nam National University of Agriculture), Le Thi Hoi (Hanoi Medical University), Nguyen Duc Thinh (National Institute for Hygiene and Epidemiology), Nguyen Thanh Phuong (RAHO6), Tran Quoc Phong (RAHO7), Nguyen Thi Kim Oanh (National Center for Veterinary Diagnostic), Bach Tuan Kiet (Dong Thap subDAH), Nguyen Van Thai (Save Viet Nam's Wildlife), Nguyen Manh Diep (Dong Nai Culture and Nature Reserve), Nguyen Xuan Dang (Tan Phu Protected Area Management Board), Nguyen The Viet and Nguyen Van Minh (Cat Tien National Park), Vo Cong Anh Tuan and Luu Trung Kien (Pu Mat National Park), Hoang Anh Tuan and Vuong Duc Hoa (Bu Gia Map National Park), Nguyen Hoang Minh Hai (Tram Chim National Park), Phan Van Truong and Nguyen Phuc Hoi (Xuan Thuy National Park), Nguyen Truong Son, Vu Dinh Thong and Nguyen Quang Truong (Institute of Ecology and Biological Resources).

In Cambodia, we extend our gratitude to Sereyrotha Ken (WCS Cambodia), Simon Mahood (WCS Cambodia), Holl Davun (General Directorate of Animal Health and Production), Erik Karlsson (Institut Pasteur du Cambodge), Doung Veasna (Institut Pasteur du Cambodge), Seng Bunnary (National Animal Health and Production Research Institute), Hak Makara (FAO Cambodia), Chin Sisaket (Phnom Tamao Wildlife Rescue Center), Angkor Center for Conservation of Biodiversity, Cambodian Applied Veterinary Epidemiology Training Program graduates, Provincial Animal Health and Production Offices, and Provincial Department of Environment Offices.

This regional effort was made possible by support from the Defense Threat Reduction Agency Biological Threat Reduction Program (BTRP) under the United States Department of Defense.

CRediT authorship contribution statement

MP, ED, AL, AP, DML conceptualize the study, supported implementation and wrote the manuscript

SHO, AEF conceptualize the study, supported implementation and reviewed the manuscript

KK, PM, SP, NTTN, PTBN, VDT, CV, SC, SS, PZ, KB supported implementation of the study and reviewed the manuscript

PP, WT, SP, KM, TS, SS, HC, PTL, NTD, VTD oversaw and facilitated the study, and reviewed the manuscript

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.160748.

References

Allen, T., Murray, K.A., Zambrana-Torrelio, C., Morse, S.S., Rondinini, C., Di Marco, M., Breit, N., Olival, K.J., Daszak, P., 2017. Global hotspots and correlates of emerging zoonotic diseases. Nat. Commun. 8, 1124.

Artois, M., Bengis, R., Delahay, R.J., Duchêne, M.-J., Paul Duff, J., Ferroglio, E., Gortazar, C., Hutchings, M.R., Kock, R.A., Leighton, F.A., Mörner, T., Smith, G.C., 2009. Wildlife disease surveillance and monitoring. In: Delahay, R.J., Smith, G.C., Hutchins, M.R. (Eds.), Management of Disease in Wild Mammals. Springer, Tokyo, pp. 187–213.

Bernstein, A.S., Ando, A.W., Loch-Temzelides, T., Vale, M.M., Li, B.V., Li, H., Busch, J., Chapman, C.A., Kinnaird, M., Nowak, K., Castro, M.C., Zambrana-Torrelio, C., Ahumada, J.A., Xiao, L., Roehrdanz, P., Kaufman, L., Hannah, L., Daszak, P., Pimm, S.L., Dobson, A.P., 2022. The costs and benefits of primary prevention of zoonotic pandemics. Sci. Adv. 8, eabl4183.

Blehert, D.S., Hicks, A.C., Behr, M., Meteyer, C.U., Berlowski-Zier, B.M., Buckles, E.L., Coleman, J.T.H., Darling, S.R., Gargas, A., Niver, R., Okoniewski, J.C., Rudd, R.J., Stone, W.B., 2009. Bat white-nose syndrome: an emerging fungal pathogen? Science 323, 227.

Brand, C.J., 2013. Wildlife mortality investigation and disease research: contributions of the USGS National Wildlife Health Center to endangered species management and recovery. EcoHealth 10, 446–454.

Chame, M., Barbosa, H.J., Gadelha, L.M., Augusto, D.A., Krempser, E., Abdalla, L., 2019. SISS-geo: leveraging citizen science to monitor wildlife health risks in Brazil. J. Healthc. Inform. Res. 3, 414–440.

Chea, S., Goutard, F.L., Pruvot, M., Thongyuan, S., 2021. Assessing the acceptability of a pilot multi-stakeholder wildlife health surveillance network in Cambodia. J. Kasetsart Veterinarians 31, 33–55.

Coker, R.J., Hunter, B.M., Rudge, J.W., Liverani, M., Hanvoravongchai, P., 2011. Emerging infectious diseases in southeast Asia: regional challenges to control. Lancet 377, 599–609.

Cukor, J., Linda, R., Václavek, P., Mahlerová, K., Šatrán, P., Havránek, F., 2020. Confirmed cannibalism in wild boar and its possible role in African Swine Fever transmission. Transbound. Emerg. Dis. 67, 1068–1073.

Delaune, D., Hul, H., Karlsson, E.A., Hassanin, A., Tey, P.O., Baidaliuk, A., Gámbaro, Priot, M., Tu, V.T., Chea, S., Keatts, L., Mazet, J., Johnson, C., Buchy, P., Dussart, P., Goldstein, T., Simon-Lorière, E., Duong, V., 2021. A novel SARS-CoV-2 related coronavirus in bats from Cambodia. Nat. Commun. 12, 6563. https://doi.org/10.1101/2021.01.26.428212.

Denstedt, E., Porco, A., Hwang, J., Nga, N.T.T., Ngoc, P.T.B., Chea, S., Khammavong, K., Milavong, P., Sours, S., Osbjer, K., Tum, S., Douangngeun, B., Theppanya, W., Van Long, N., Thanh Phuong, N., Tin Vinh Quang, L., Van Hung, V., Hoa, N.T., Le Anh, D., Fine, A., Pruvot, M., 2021. Detection of African Swine Fever virus in free-ranging wild boar in Southeast Asia. Transbound. Emerg. Dis. 68, 2669–2675.

Dobson, A.P., Pimm, S.L., Hannah, L., Kaufman, L., Ahumada, J.A., Ando, A.W., Bernstein, A., Busch, J., Daszak, P., Engelmann, J., Kinnaird, M.F., Li, B.V., Loch-Temzelides, T., Lovejoy, T., Nowak, K., Roehrdanz, P.R., Vale, M.M., 2020. Ecology and economics for pandemic prevention. Science 369, 379–381.

Fine, A.E., Pruvot, M., Benfield, C.T.O., Caron, A., Cattoli, G., Chardonnet, P., Dioli, M., Dulu, T., Gilbert, M., Kock, R., Lubroth, J., Mariner, J.C., Ostrowski, S., Parida, S., Fereidouni, S., Shiilegdamba, E., Sleeman, J.M., Schulz, C., Soula, J.-J., Van der Stede, Y., Tekola, B.G., Walzer, C., Zuther, S., Njeumi, F., Participants, Meeting, 2020. Eradication of peste des petits ruminants virus and the wildlife-livestock interface. Front. Vet. Sci. 7, 50.

Fisher, M.C., Garner, T.W.J., 2020. Chytrid fungi and global amphibian declines. Nat. Rev. Microbiol. 18, 332–343.

Food and Agriculture Organization of the United Nations, World Organization for Animal Health, World Health Organization, 2019. Taking a multisectoral One Health approach: a tripartite guide to addressing zoonotic diseases in countries. https://www.woah.org/app/uploads/2021/03/en-tripartitezoonosesguide-webversion.pdf (accessed May 2022).

Food and Agriculture Organization of the United Nations, World Organisation for Animal Health, World Health Organization, United Nations Environment Program, 2022. Memorandum of understanding between the Food and Agriculture Organization of the United Nations, the World Organisation for Animal Health, the World Health Organization and the United Nations Environment Programme regarding cooperation to combat health risks at the animal-human-ecosystem interface in the context of the "One Health" approach and inclusing antimicrobial resistance. https://www.fao.org/3/cb9403en/cb9403en.pdf (accessed May 2022).

Global Health Security Agenda, 2018. Global Health Security Agenda (GHSA) 2024 Framework. (accessed August 2020) https://ghsagenda.org/wp-content/uploads/2020/06/ghsa2024-framework.pdf.

Goutard, F., Calba, C., Chea, S., Antoine-Moussiaux, N., Pruvot, M., Schulz, K., Peyre, M., 2022. The use of participatory methods in the evaluation of health surveillance systems. In: Peyre, M., Roger, F., Goutard, F. (Eds.), Principles for Evaluation of One Health Surveillance: The EVA Book. Springer International Publishing, Cham, pp. 163–177.

Gruetzmacher, K., Karesh, W.B., Amuasi, J.H., Arshad, A., Farlow, A., Gabrysch, S., Jetzkowitz, J., Lieberman, S., Palmer, C., Winkler, A.S., Walzer, C., 2020. The Berlin principles on one health – bridging global health and conservation. Sci. Total Environ. 142919.

Harvell, C.D., Montecino-Latorre, D., Caldwell, J.M., Burt, J.M., Bosley, K., Keller, A., Heron, S.F., Salomon, A.K., Lee, L., Pontier, O., Pattengill-Semmens, C., Gaydos, J.K., 2019. Disease epidemic and a marine heat wave are associated with the continental-scale collapse of a pivotal predator (Pycnopodia helianthoides). Sci. Adv. 5, eaau7042.

Huong, N.Q., Nga, N.T.T., Van Long, N., Luu, B.D., Latinne, A., Pruvot, M., Phuong, N.T., Quang, L.T.V., Van Hung, V., Lan, N.T., Hoa, N.T., Minh, P.Q., Diep, N.T., Tung, N., Ky, V.D., Roberton, S.I., Thuy, H.B., Van Long, N., Gilbert, M., Wicker, L., Mazet, J.A.K., Johnson, C.K., Goldstein, T., Tremeau-Bravard, A., Ontiveros, V., Joly, D.O., Walzer, C., Fine, A.E., Olson, S.H., 2020. Coronavirus testing indicates transmission risk increases along wildlife supply chains for human consumption in Viet Nam, 2013-2014. PLoS One 15, e0237129.

International Society for Infectious Diseases - The Program for Monitoring Emerging Diseases, 2021. Lumpy Skin Disease - Asia (13): Thailand (Uthai Thani) wild cattle. https://promedmail.org/promed-post/?id=8540224 (accessed August 2020).

Keatts, L.O., Robards, M., Olson, S.H., Hueffer, K., Insley, S.J., Joly, D.O., Kutz, S., Lee, D.S., Chetkiewicz, C.-L.B., Lair, S., Preston, N.D., Pruvot, M., Ray, J.C., Reid, D., Sleeman, J.M., Stimmelmayr, R., Stephen, C., Walzer, C., 2021. Implications of zoonoses from hunting and use of wildlife in North American Arctic and boreal biomes: pandemic potential, monitoring, and mitigation. Front. Public Health 9, 627654.

Kelly, T.R., Karesh, W.B., Johnson, C.K., Gilardi, K.V.K., Anthony, S.J., Goldstein, T., Olson, S.H., Machalaba, C., PREDICT Consortium, Mazet, J.A.K., 2017. One Health proof of concept: bringing a transdisciplinary approach to surveillance for zoonotic viruses at the human-wild animal interface. Prev. Vet. Med. 137, 112–118.

Kelly, T.R., Pandit, P.S., Carion, N., Dombrowski, D.F., Rogers, K.H., McMillin, S.C., Clifford, D.L., Riberi, A., Ziccardi, M.H., Donnelly-Greenan, E.L., Johnson, C.K., 2021. Early detection of wildlife morbidity and mortality through an event-based surveillance system. Proc. Biol. Sci. 288, 20210974.

Kuchipudi, S.V., Surendran-Nair, M., Ruden, R.M., Yon, M., Nissly, R.H., Vandegrift, K.J., Nelli, R.K., Li, L., Jayarao, B.M., Maranas, C.D., Levine, N., 2022. Multiple spillovers from humans and onward transmission of SARS-CoV-2 in white-tailed deer. Proc. Natl. Acad. Sci. U. S. A. 119, e2121644119.

Kuisma, E., Olson, S.H., Cameron, K.N., Reed, P.E., Karesh, W.B., Ondzie, A.I., Akongo, M.-J., Kaba, S.D., Fischer, R.J., Seifert, S.N., Muñoz-Fontela, C., Becker-Ziaja, B., Escudero-Pérez, B., Goma-Nkoua, C., Munster, V.J., Mombouli, J.-V., 2019. Long-term wildlife mortality surveillance in northern Congo: a model for the detection of Ebola virus disease epizootics. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 374, 20180339.

Kutz, S., Tomaselli, M., 2019. "Two-eyed seeing" supports wildlife health. Science 21, 1135–1137.

LACANET, 2016. One Health Network South East Asia. (accessed May 2022) http://www.onehealthsea.org/lacanet/.

Lawson, B., Neimanis, A., Lavazza, A., López-Olvera, J.R., Tavernier, P., Billinis, C., Duff, J.P., Mladenov, D.T., Rijks, J.M., Savić, S., Wibbelt, G., Ryser-Degiorgis, M.-P., Kuiken, T., 2021. How to start up a national wildlife health surveillance programme. Animals 11.

Leighton, F.A., Wobeser, G.A., Barker, I.K., Daoust, P.Y., Martineau, D., 1997. The Canadian Cooperative Wildlife Health Centre and surveillance of wild animal diseases in Canada. Can. Vet. J. 38, 279–284.

Li, H., Chen, Y., Machalaba, C.C., Tang, H., Chmura, A.A., Fielder, M.D., Daszak, P., 2021. Wild animal and zoonotic disease risk management and regulation in China: examining gaps and one health opportunities in scope, mandates, and monitoring systems. One Health 13, 100301.

Luskin, M.S., Meijaard, E., Surya, S., Sheherazade, Walzer, C., Linkie, M., 2021. African Swine Fever threatens Southeast Asia's 11 endemic wild pig species. Conserv. Lett. 14, e12784.

Machalaba, C., Uhart, M., Ryser-Degiorgis, M.-P., Karesh, W.B., 2021. Gaps in health security related to wildlife and environment affecting pandemic prevention and preparedness, 2007–2020. Bull. World Health Organ. 99, 342–350B.

McIver, D.J., Silithammavong, S., Theppangna, W., Gillis, A., Douangngeun, B., Khammavong, K., Singhalath, S., Duong, V., Buchy, P., Olson, S.H., Keatts, L., Fine, A.E., Greatorex, Z., Gilbert, M., LeBreton, M., Saylors, K., Joly, D.O., Rubin, E.M., Lange, C.E., 2020. Coronavirus surveillance of wildlife in the lao People's Democratic Republic detects viral RNA in rodents. Arch. Virol. 165, 1869–1875.

Nga, N.T.T., Latinne, A., Thuy, H.B., Van Long, N., Ngoc, P.T.B., Anh, N.T.L., Van Thai, N., Phuong, T.Q., Van Thai, H., Hai, L.K., Long, P.T., Phuong, N.T., Van Hung, V., Quang, L.T.V., Lan, N.T., Hoa, N.T., Johnson, C.K., Mazet, J.A.K., Roberton, S.I., Walzer, C., Olson, S.H., Fine, A.E., 2022. Evidence of SARS-CoV-2 related coronaviruses circulating in Sunda pangolins (Manis javanica) confiscated from the illegal wildlife trade in Viet Nam. Front. Public Health 10, 826116.

Peacock, S.J., Mavrot, F., Tomaselli, M., Hanke, A., Fenton, H., Nathoo, R., Aleuy, O.A., Di Francesco, J., Aguilar, X.F., Jutha, N., Kafle, P., Mosbacher, J., Goose, A., Ekaluktutiak Hunters and Trappers Organization, Kugluktuk Angoniatit Association, Olokhaktomiut Hunters and Trappers Committee, Kutz, S.J., 2020. Linking co-monitoring to co-management: bringing together local, traditional, and scientific knowledge in a wildlife status assessment framework. Arct. Sci. 6, 247–266.

Probst, C., Globig, A., Knoll, B., Conraths, F.J., Depner, K., 2017. Behaviour of free ranging wild boar towards their dead fellows: potential implications for the transmission of African swine fever. R. Soc. Open Sci. 4, 170054.

Pruvot, M., Fine, A.E., Hollinger, C., Strindberg, S., Damdinjav, B., Buuveibaatar, B., Chimeddorj, B., Bayandonoi, G., Khishgee, B., Sandag, B., Narmandakh, J., Jargalsaikhan, T., Bataa, B., McAloose, D., Shatar, M., Basan, G., Mahapatra, M., Selvaraj, M., Parida, S., Njeumi, F., Kock, R., Shiilegdamba, E., 2020. Outbreak of peste des petits ruminants among critically endangered Mongolian saiga and other wild ungulates, Mongolia, 2016–2017. Emerg. Infect. Dis. 26, 51–62.

Russell, R.E., DiRenzo, G.V., Szymanski, J.A., Alger, K.E., Grant, E.H., 2020. Principles and mechanisms of wildlife population persistence in the face of disease. Front. Ecol. Evol. 8, 569016.

Ryser-Degiorgis, M.P., 2013. Wildlife health investigations: needs, challenges and recommendations. BMC Vet. Res. 9, 223.

de Sadeleer, N., Godfroid, J., 2020. The story behind COVID-19: animal diseases at the crossroads of wildlife, livestock and human health. Eur. J. Risk Regul. 11, 210–227.

Sleeman, J.M., Brand, C.J., Wright, S.D., 2012. Strategies for wildlife disease surveillance. In: Aguirre, A.A., Ostfeld, R.S., Daszak, P. (Eds.), New Directions in Conservation Medicine: Applied Cases in Ecological Health. Oxford University Press, New York, pp. 539–551.

SMART Partnership, 2021. SMART Annual Report 2019–2020. (accessed May 2022) https://drive.google.com/file/d/1gngpGbtlmRo3VkUpBxn5pXdfLp1TG8wx/view.
Stallknecht, D.E., 2007. Impediments to wildlife disease surveillance, research, and diagnostics. Curr. Top. Microbiol. Immunol. 315, 445–461.
Stephen, C., 2015. The Canadian wildlife health cooperative: addressing wildlife health challenges in the 21st century. Can. Vet. J. 56, 925–927.
Stephen, C., Sleeman, J., Nguyen, N., Zimmer, P., Duff, J.P., Gavier-Widén, D., Grillo, T., Lee, H., Rijks, J.M., Ryser-Degiorgis, M.P., Tana, T., Uhart, M., 2018. Proposed attributes of national wildlife health programmes. Rev. Sci. Tech. 37, 925–936.
Tambo, E., Ai, L., Zhou, X., Chen, J.-H., Hu, W., Bergquist, R., Guo, J.-G., Utzinger, J., Tanner, M., Zhou, X.-N., 2014. Surveillance-response systems: the key to elimination of tropical diseases. Infect. Dis. Poverty 3, 17.
VanderWaal, K., Morrison, R.B., Neuhauser, C., Vilalta, C., Perez, A.M., 2017. Translating big data into smart data for veterinary epidemiology. Front. Vet. Sci. 4, 110.
Vora, N.M., Hannah, L., Lieberman, S., Vale, M.M., Plowright, R.K., Bernstein, A.S., 2022. Want to prevent pandemics? Stop spillovers. Nature 605, 419–422.
White, R.J., Razgour, O., 2020. Emerging zoonotic diseases originating in mammals: a systematic review of effects of anthropogenic land-use change. Mamm. Rev. 50, 336–352.
Wilcove, D.S., Giam, X., Edwards, D.P., Fisher, B., Koh, L.P., 2013. Navjot's nightmare revisited: logging, agriculture, and biodiversity in Southeast Asia. Trends Ecol. Evol. 28, 531–540.
Woods, R., Reiss, A., Cox-Witton, K., Grillo, T., Peters, A., 2019. The importance of wildlife disease monitoring as part of global surveillance for zoonotic diseases: the role of Australia. Trop. Med. Infect. Dis. 4, 29.
World Health Organization, 2008. International Health Regulations (2005). World Health Organization (accessed May 2022) https://www.who.int/health-topics/international-health-regulations#tab=tab_1.
World Health Organization, UN Environment Program, Convention on Biological Diversity, 2015. Connecting global priorities: biodiversity and human health. A state of knowledge review. https://www.cbd.int/health/SOK-biodiversity-en.pdf (accessed May 2022).
World Organisation for Animal Health, 2010. Training Manual on Wildlife Diseases and Surveillance. (accessed May 2022) https://www.woah.org/fileadmin/Home/eng/Internationa_Standard_Setting/docs/pdf/WGWildlife/A_Training_Manual_Wildlife.pdf.
World Organisation for Animal Health, 2015. Training Manual on Surveillance and International Reporting of Diseases in Wild Animals. (accessed May 2022) https://www.woah.org/fileadmin/Home/eng/Internationa_Standard_Setting/docs/pdf/WGWildlife/A_Training_Manual_Wildlife_2.pdf.
World Organisation for Animal Health, 2017. Training Manual on Wildlife Health Risk Assessment in Support of Decisions and Policies. (accessed July 2020) https://rr-africa.woah.org/wp-content/uploads/2020/07/a_training_manual_wildlife_3.pdf.
World Organisation for Animal Health, 2017. Training Manual on Wildlife Disease Outbreak investigations. https://www.woah.org/app/uploads/2021/03/a-training-manual-wildlife-4.pdf (accessed May 2022).
World Organisation for Animal Health, 2018. Training Manual on Wildlife Health Information Management. (accessed July 2020) https://www.woah.org/fileadmin/Home/eng/Internationa_Standard_Setting/docs/pdf/WGWildlife/A_Training_Manual_Wildlife_5.pdf.
World Organisation for Animal Health, 2021. OIE Wildlife Health Framework "Protecting Wildlife Health to Achieve One Health". (accessed May 2022) https://www.woah.org/fileadmin/Home/eng/Internationa_Standard_Setting/docs/pdf/WGWildlife/A_Wildlifehealth_conceptnote.pdf.